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A Proposal for Grading Plutonium Mixtures

ANS Executive Panel Entitled, “Not All Plutonium is Created Equal?”

Charles G. Bathke

6/13/2022

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Outline

- This presentation will give:
  - A rationale for why all plutonium poses a safeguards and security risk
  - A proposal for providing some relief for plutonium mixtures, such as MOX, based on dilution

A Rationale for Why All Plutonium Poses a Safeguards and Security Risk

- An answer to why all plutonium metal poses a safeguards and security risk lies in bare critical mass (BCM)
- The reason BCM is relevant is:
  - NED fuel must be capable of going quickly from subcritical to supercritical to achieve nuclear yield
  - A material that has a BCM is called fissible
  - Fissible materials can be made to go from subcritical to supercritical
- Then, a necessary, but not sufficient condition for a material to be weapon usable is that it be fissible
  - All weapon usable materials are fissible
  - Not all fissible materials are weapon usable

A Rationale for Why All Plutonium Poses a Safeguards and Security Risk (cont'd)

- Next is a list of fissible isotopes with half-lives greater three years
  - Three years was chosen to eliminate isotopes with that are in very small concentration because of their short half-lives (e.g., ^{242}Cm)
- List of fissible isotopes
  - Is ordered by increasing BCM
  - Is then put into groups
  - Groups are anchored to IAEA's boundary between HEU and LEU, which is 20% ^{235}U which has a BCM of ~800 kg
  - Grouped by half decades in BCM (M)
    - M < 8 kg
    - 8 < M < 25 kg
    - 25 < M < 80
    - 80 < M < 250
    - 250 < M < 800
    - 800 < M

List of Fissible Isotopes[a] with Half-Lives > 3 years

Isotope	ρ (g/cc)	$\tau_{1/2}$ (y)[b]	Decay Mode[b]	Heating Rate (W/g)	M (kg)
M < 8 kg					
^{243}Cm	13.51	29.1	α	$1.89(10)^{0}$	5.91
^{232}U	18.95	68.9	α	$6.87(10)^{-1}$	5.97
^{249}Cf	15.1	351	α	$1.90(10)^{-1}$	6.85
^{236}Np	20.45	$1.53(10)^{5}$	ε, β^-	$2.66(10)^{-5}$	7.14
8 < M < 25 kg					
^{238}Pu	19.84	87.7	α	$5.67(10)^{-1}$	8.18
^{247}Cm	13.51	$1.56(10)^{7}$	α	$2.96(10)^{-6}$	8.76
^{239}Pu	19.84	24110	α	$1.92(10)^{-3}$	9.98
^{248}Bk	14.79	> 9	α	$7.68(10)^{2}$	10.02
^{242m}Am	13.69	141	IT	0	10.88
^{245}Cm	13.51	8423	α	$5.70(10)^{-3}$	11.93
^{241}Pu	19.84	14.3	β^-	$3.19(10)^{-3}$	13.01
^{251}Cf	15.1	898	α	$5.66(10)^{-2}$	14.31
^{233}U	18.95	$1.59(10)^{5}$	α	$2.81(10)^{-4}$	15.22
^{244}Cm	13.51	18.1	α	$2.83(10)^{0}$	17.70
^{250}Cf	15.1	13.1	α	$4.06(10)^{0}$	18.33
25 < M < 80 kg					
^{240}Pu	19.84	6561	α	$7.09(10)^{-3}$	37.29
^{235}U	18.95	$7.04(10)^{8}$	α	$5.66(10)^{-8}$	46.33
^{246}Cm	13.51	4706	α	$1.01(10)^{-2}$	46.88
^{237}Np	20.45	$2.14(10)^{6}$	α	$2.15(10)^{-5}$	58.75
^{248}Cm	13.51	$3.48(10)^{5}$	α	$5.29(10)^{-4}$	63.32
^{241}Am	13.69	432.6	α	$1.14(10)^{-1}$	66.70
^{242}Pu	19.84	$3.75(10)^{5}$	α	$1.13(10)^{-4}$	74.33
80 < M < 250 kg					
^{244}Pu	19.84	$8.00(10)^{7}$	α	$5.14(10)^{-7}$	103.06
^{234}U	18.95	$2.46(10)^{5}$	α	$1.80(10)^{-4}$	126.06
^{243}Am	13.69	7370	α	$6.41(10)^{-3}$	178.23
250 < M < 800 kg					
^{247}Bk	14.79	1380	α	$3.59(10)^{-2}$	406.32
800 kg < M					
^{250}Cm	13.51	8300	SF, α	$6.01(10)^{-2}$	982.85
^{229}Th	11.72	7932	α	$6.51(10)^{-3}$	29850.39

[a] Using ENDF/B-VIII.0 cross sections

[b] http://www.nndc.bnl.gov/wallet/wccurrent.html

^{233}U and ^{235}U Appear in Different Groups

Isotope	ρ (g/cc)	$\tau_{1/2}$ (y)[b]	Decay Mode[b]	Heating Rate (W/g)	M (kg)
M < 8 kg					
^{243}Cm	13.51	29.1	α	$1.89(10)^{0}$	5.91
^{232}U	18.95	68.9	α	$6.87(10)^{-1}$	5.97
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Isotope	ρ (g/cc)	$\tau_{1/2}$ (y)[b]	Decay Mode[b]	Heating Rate (W/g)	M (kg)
25 < M < 80 kg					
^{240}Pu	19.84	6561	α	$7.09(10)^{-3}$	37.29
^{235}U	18.95	$7.04(10)^{8}$	α	$5.66(10)^{-8}$	46.33
^{246}Cm	13.51	4706	α	$1.01(10)^{-2}$	46.88
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[a] Using ENDF/B-VIII.0 cross sections

[b] http://www.nndc.bnl.gov/wallet/wccurrent.html

- The above grouping is consistent with the grouping of ^{233}U separate from ^{235}U in the US DOE Graded Safeguards Table (DOE O 474.2 Chg. 4) and the IAEA Categorization Table (INFCIRC/225/Rev 5)

^{238}Pu, ^{239}Pu, and ^{241}Pu Appear in ^{233}U Group, and ^{240}Pu and ^{241}Pu Appear in ^{235}U Group

Isotope	ρ (g/cc)	$\tau_{1/2}$ (y)[b]	Decay Mode[b]	Heating Rate (W/g)	M (kg)
M < 8 kg					
^{243}Cm	13.51	29.1	α	$1.89(10)^{0}$	5.91
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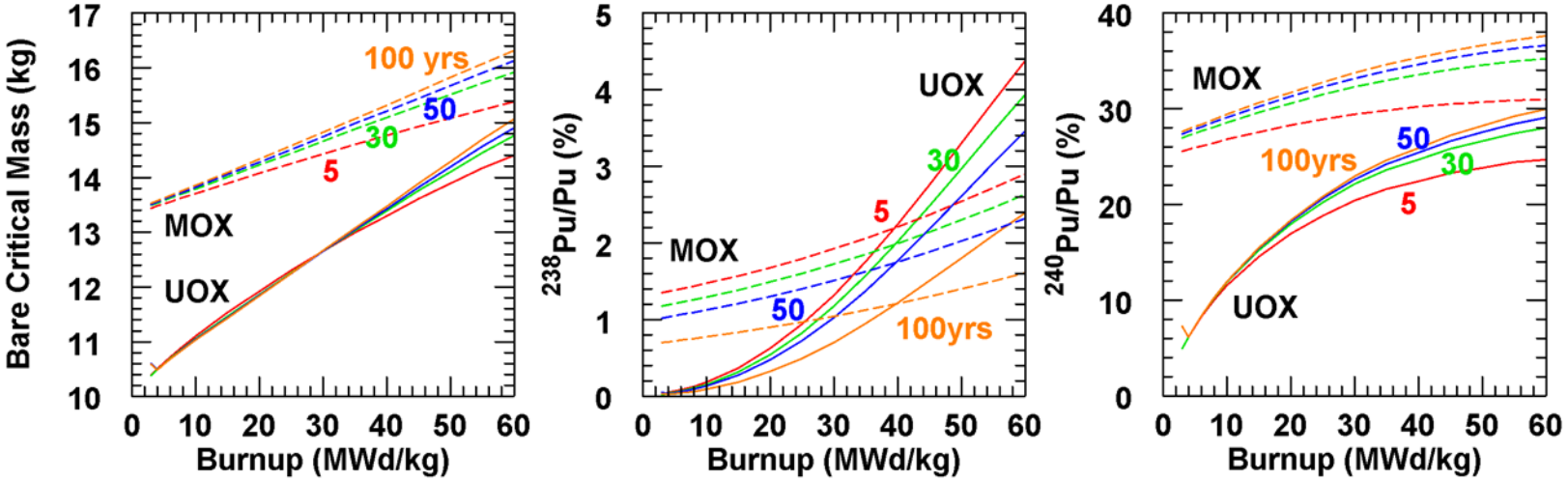
[a] Using ENDF/B-VIII.0 cross sections

[b] http://www.nndc.bnl.gov/wallet/wccurrent.html

- The above grouping is consistent with the grouping of Pu and ^{233}U together, but separate from ^{235}U in the US DOE Graded Safeguards Table (DOE O 474.2 Chg. 4) and the IAEA Categorization Table (INFCIRC/225/Rev 5)

What Does Pu from LWRs Look Like?



- Above results are the BCM (left), ^{238}Pu content (center), and ^{240}Pu content (right) of Pu in spent fuel as a function of burnup for various cooling times:
  - UOX refers to Pu obtained by processing spent UOX fuel
  - MOX refers to Pu obtained by processing spent MOX fuel (single recycle)
- According to "Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives," DOE0NN-0007, pp. 37, 38, U.S. Department of Energy (1997), ^{238}Pu and ^{240}Pu are not an obstacle to nuclear explosives devices
- When separated, the plutonium from spent UOX and MOX has a smaller BCM than ^{235}U; it is even in a more-attractive, lower-BCM group than ^{235}U and requires safeguards and security

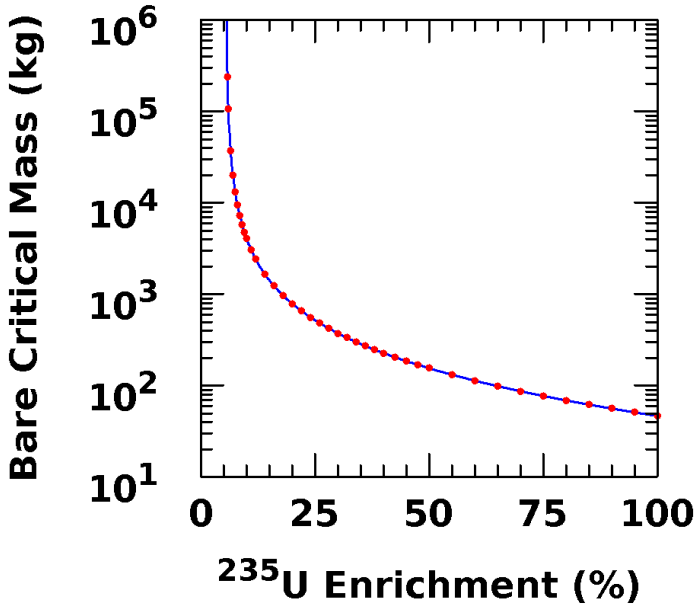
The IAEA Has Provided a Way to Grade ^{235}U

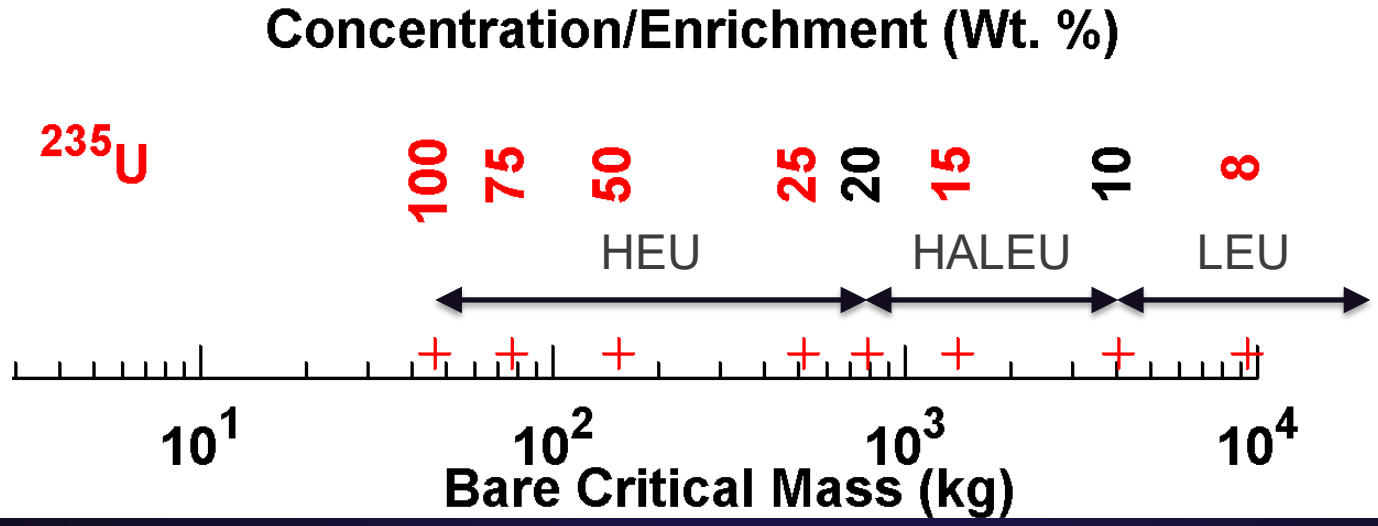
- The IAEA Categorization Table contains three grades of ^{235}U:
  - U < 10% ^{235}U
  - 10% ^{235}U ≤ U < 20% ^{235}U
  - U ≥ 20% ^{235}U

Material	Form	Category I	Category II	Category III[c]
2. Uranium-235 (^{235}U)	Unirradiated[b]			
	– Uranium enriched to 20% ^{235}U or more	5 kg or more	Less than 5 kg but more than 1 kg	1 kg or less but more than 15 g
	– Uranium enriched to 10% ^{235}U but less than 20% ^{235}U		10 kg or more	Less than 10kg but more than 1 kg
	– Uranium enriched above natural, but less than 10% ^{235}U			10 kg or more

Proposal

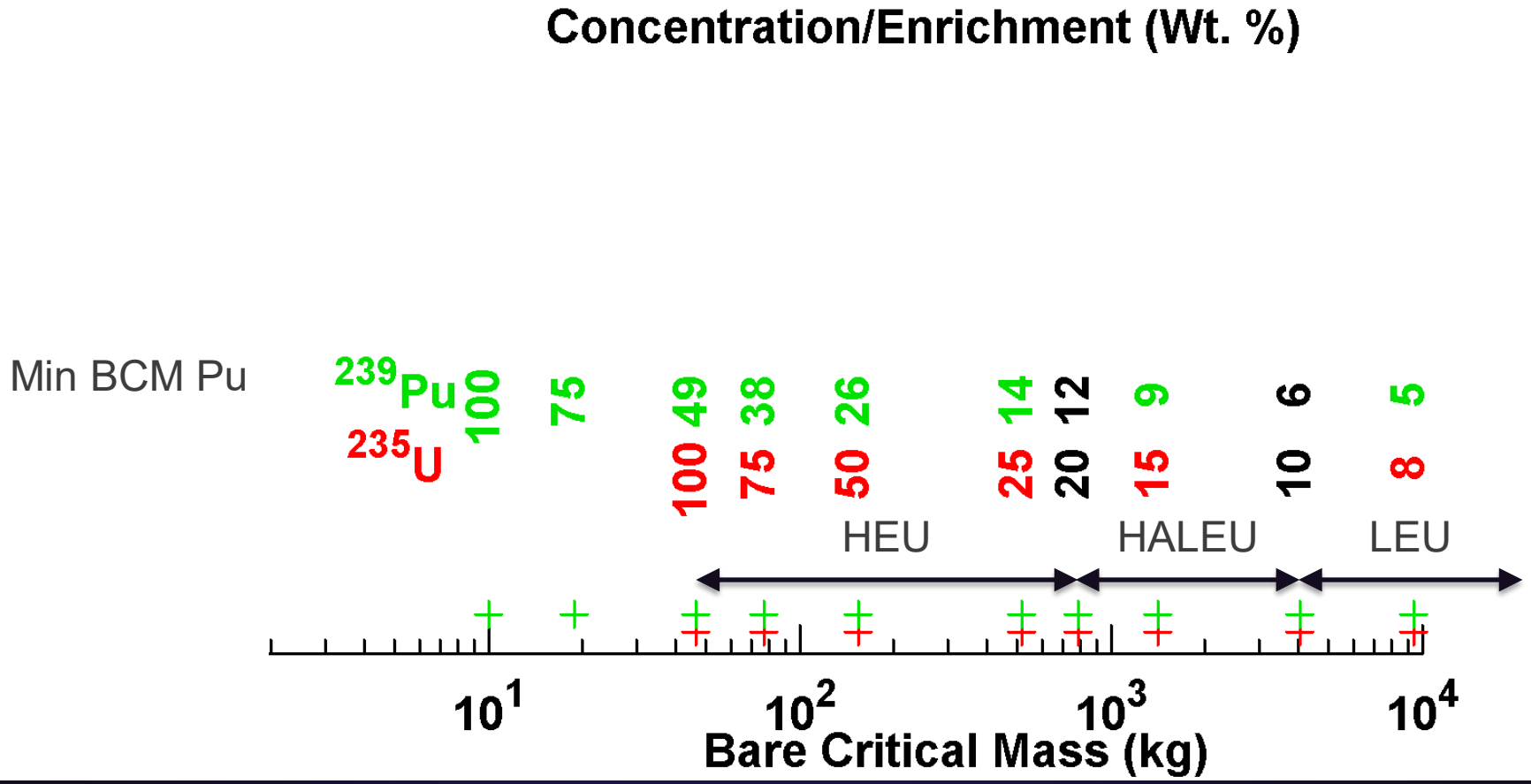
- Invert EU BCM plot at right
- Select plutonium dilution grades that are equivalent in BCM to a set of enriched uranium grades
- For example, select IAEA HEU, HALEU, and LEU





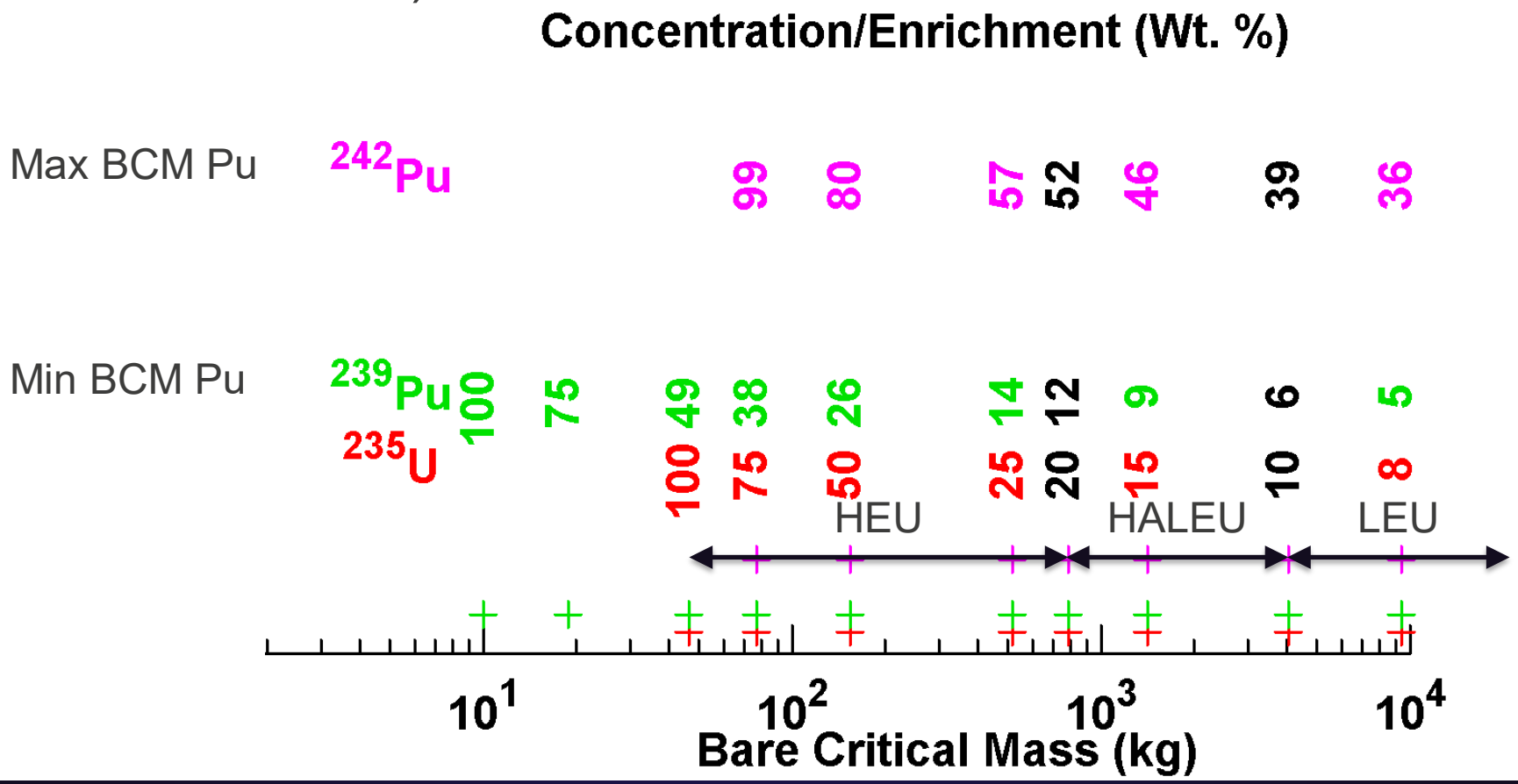
Proposal (cont'd)

- Add BCM of a Pu isotopic vector (e.g., ^{239}Pu diluted with DU)



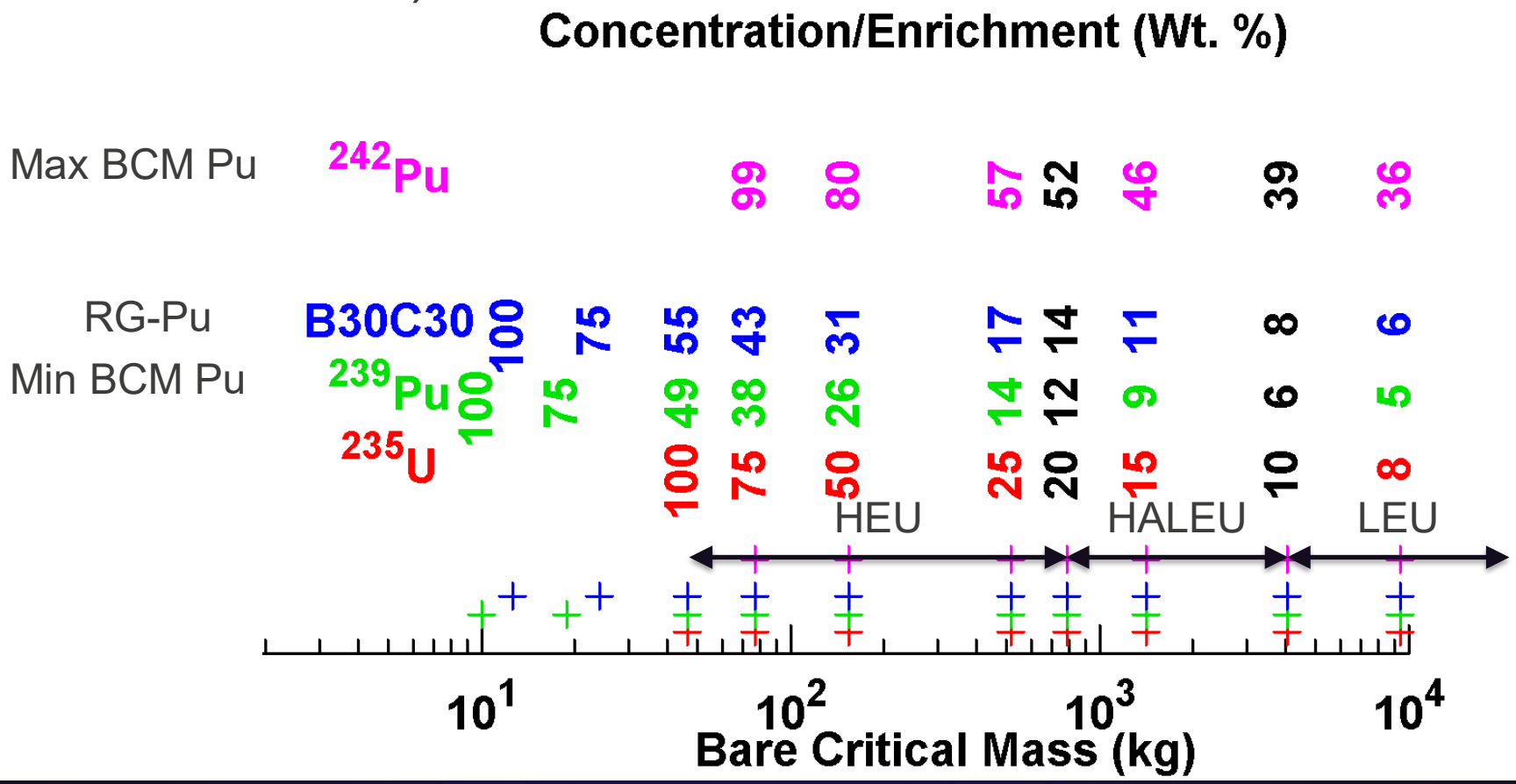
Proposal (cont'd)

- Add BCM of a Pu isotopic vector (e.g., ^{239}Pu, ^{242}Pu, diluted with DU)



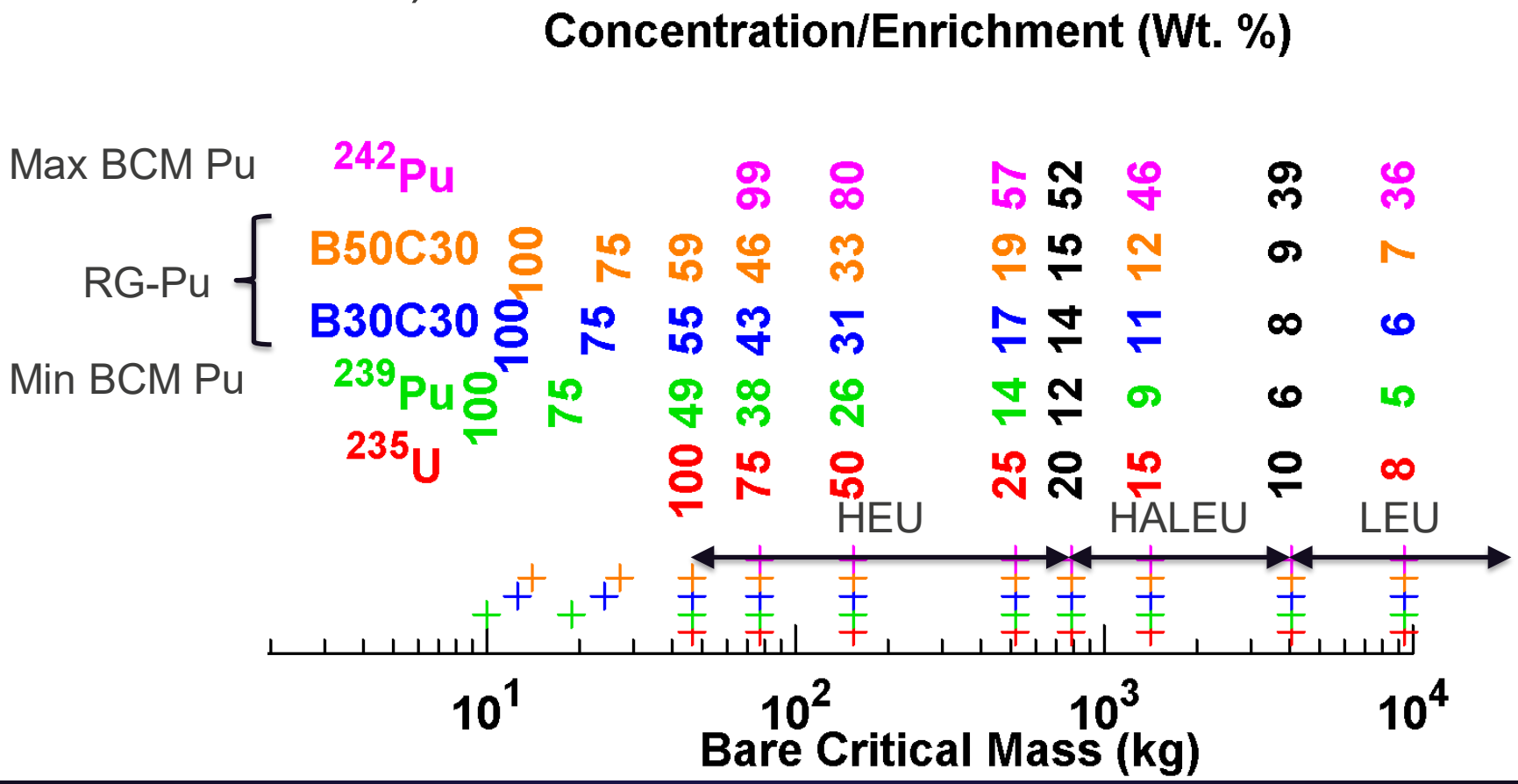
Proposal (cont'd)

- Add BCM of a Pu isotopic vector (e.g., ^{239}Pu, ^{242}Pu, from SUOX burned to 30 MWd/kg and cooled 30 yrs diluted with DU)



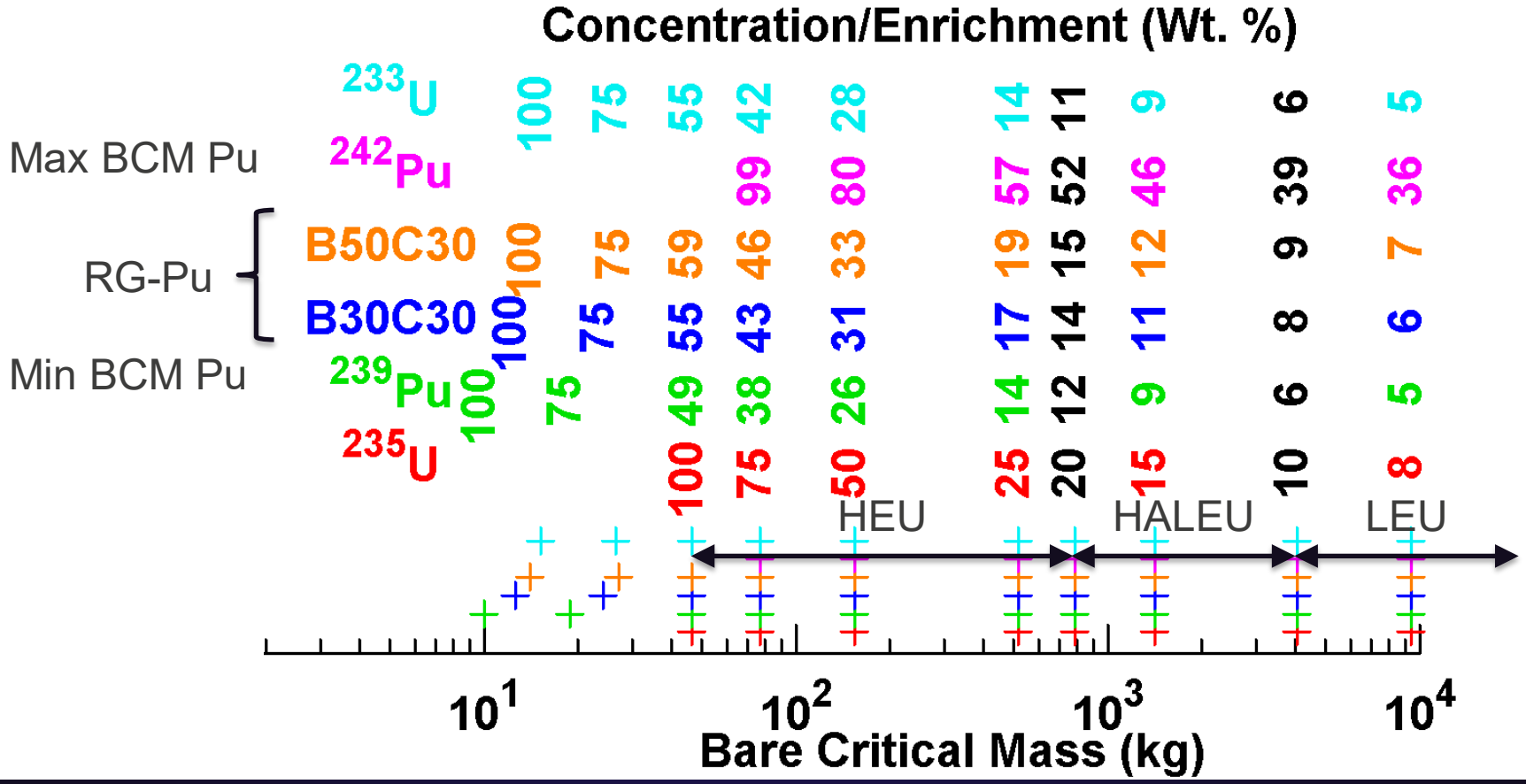
Proposal (cont'd)

- Add BCM of a Pu isotopic vector (e.g., ^{239}Pu, ^{242}Pu, from SUOX burned to 30 or 50 MWd/kg and cooled 30 yrs diluted with DU)



Proposal (cont'd)

- Add BCM of a Pu isotopic vector (e.g., ^{239}Pu, ^{242}Pu, Pu from SUOX burned to 30 or 50 MWd/kg and cooled 30 yrs diluted with DU)



Caveats

- Even though Sect. 3.42. of the IAEA's INFCIRC/225/Rev 5 encourages a graded approach to physical protection, diluted plutonium is still considered direct use material by the IAEA's Safeguards Glossary (2001 Edition), Sect. 4.25
- Diluted plutonium is less attractive than undiluted plutonium, but **it is not proliferation resistant**
- Plutonium dilution does add an additional layer of protection as part of a defense in depth approach to safeguards and security
- Safeguards and security are still needed for IAEA direct use materials
- Plutonium diluted with DU differs significantly from either ^{233}U or ^{235}U diluted with DU
  - Diluted Pu requires processing
  - ^{233}U and ^{235}U diluted with DU require enrichment, which is much more difficult and energy intensive than processing

Conclusion

- This presentation provided:
  - A rationale for why all plutonium poses a safeguards and security risk
  - A proposal for providing some relief for plutonium mixtures, such as MOX, based on dilution
    - Determine plutonium concentration in a mixture that has the same bare critical mass as the desired uranium grade
    - Algorithm also applies to ^{233}U from spent thorium fuel